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ABSTRACT

The feasibility of performing an on-orbit refueling (OOR) operation to extend the orbital lifetime of the NASA Goddard Space Flight Center (GSFC) Gamma Ray Observatory (GRO) was investigated by TRW, the GRO mission contractor. This study shows that an OOR capability could be integrated into the GRO operational design early in the Phase D development with only minor cost impact and no schedule impact. In this approach, the GRO OOR design would be developed to achieve operational compatibility with the JSC/STS-developed Orbital Refueling System.

INTRODUCTION

Under the direction of the GRO project office at NASA GSFC, TRW performed a 4-month, three-phase feasibility study to identify technical, cost, and schedule impact for incorporating OOR into the GRO operational baseline. The study began in mid-February 1983 and was completed by mid-June.

OOR STUDY OVERVIEW

The three-phase GRO OOR feasibility study was initiated concurrently with the GRO Phase D contract go-ahead (February 1983). TRW, the Phase D mission contractor, recently had completed an 18-month GRO Phase C contract that established a baseline system and subsystem design concept for the GRO mission. The three phases of the OOR study were:

- Phase I — Concept Evaluation/Selection
- Phase II — Concept Definition
- Phase III — Costing.

This paper presents a brief overview of the GRO, a description of the GRO propulsion subsystem whose baseline design could be modified by the incorporation of OOR, and the results from Phases I and II of the study.

GRO DESCRIPTION

The GRO is a large, 28-foot-long, 15-foot-diameter scientific payload weighing approximately 33,000 pounds. GRO, scheduled for launch aboard STS in the second quarter of 1988, will perform a 27-month mission at LEO altitude of 350 to 450 km. The mission concept is summarized in Figures 1 and 2. Figure 3 provides an outline of the various hardware elements that make up the GRO space segment. Figure 4 is a sketch of the GRO in the deployed configuration.

PROPULSION SUBSYSTEM BASELINE

The GRO monopropellant hydrazine propulsion subsystem provides impulse for orbit altitude change, orbit maintenance (drag makeup), attitude control, and controlled reentry. The baseline GRO propulsion subsystem (Figure 5), which does not include the OOR capability, consists of:

- Four diaphragm expulsion tanks, each with a capacity of 950 pounds
- Four 100-pound orbit adjust thrusters and eight 5-pound attitude control thrusters, assembled in pairs known as dual thruster modules (DTM)
- Two propellant distribution modules (PDM) containing latching isolation valves, filters, and pressure transducers
- Two propellant/pressurant fill and drain modules (FDM).

The tanks, thrusters, modules, and interconnecting lines are mounted on a separate propulsion module structure which is attached to the observatory primary structure. The propulsion subsystem, which features all-welded line and component joints, is configured to meet the safety requirements of NHB 1700.7A.

PHASE I — CONCEPT EVALUATION/SELECTION

The primary objective of Phase I was the evaluation and selection of the design approach for propellant transfer. Design simplicity, operational simplicity, and cost considerations dictated selection of the ullage recompression (UR) technique. This choice met with the approval of NASA/JSC.

The other Phase I objectives were to:

- Establish a preliminary refueling timeline
- Conceptualize a quick-disconnect coupling for refueling operation
- Identify GRO/STS OOR interfaces
- Identify safety issues.

The Phase I OOR study ground rules and assumptions are listed in Figure 6.

Refueling Approaches

Three methods of propellant transfer were considered for GRO: ullage recompression, ullage displacement, and ullage vent/repressurization. These were compared on the basis of mechanical and operational complexity; however, other factors such as ullage gas heat dissipation and safety were also considered in the trade study. Each refueling approach is briefly discussed below, along with its advantages and disadvantages.

Ullage Recompression. In this approach, the pressurant gas remains in the propellant tanks during refueling. Propellant is transferred against an increasing ullage pressure as the incoming hydrazine compresses the ullage gas.

Advantages include:

- Mechanical simplicity. No provision is required for purging and repressurizing the tank ullage.
- Operational simplicity. Only propellant is transferred.
- Propellant flow meters are not required. Pressure volume temperature (PVT) data can be used to measure fuel load.
- Refueling and repressurization are accomplished simultaneously.

The ullage recompression method allows filling all four tanks simultaneously since the ullage pressure will serve to evenly distribute the incoming propellant among the four tanks. A full load of fuel should restore the system to near-BOL operating pressure.

Disadvantages include:

- Ullage compression requires a large heat dissipation.
- The pressure of the refueling supply must be higher than the BOL propellant tank pressure (in this case, greater than 350 psia).

Ullage Vent/Repressurization. In the vent/repressurize scheme, the tank ullage is vented to zero pressure before transferring propellant. Thus, the supply pressure need only be high enough to overcome frictional losses in the refueling lines. Each tank must be filled individually, and propellant must be carefully metered to ensure uniform distribution of fuel among the tanks. Once filled, the tanks are simultaneously repressurized.

Advantages include:

- Low-pressure propellant supply
- Lower heat of compression than ullage recompression during repressurization.

Disadvantages include:

- Greater operational complexity than ullage recompression
- More mechanical complexity than ullage recompression
- Propellant metering required.

Ullage Displacement. This approach is a compromise between ullage recompression and ullage vent/repressurization. The incoming propellant displaces an equal volume of pressurant as the tanks are refilled. Thus, the process occurs at constant pressure. After the propellant transfer is complete, the tank ullages are repressurized.

Advantages include:

- Constant-pressure propellant transfer
- Lowest compression heating of the three methods
- Less operational complexity than ullage vent/repressurization
- Simultaneous tank fill possible.

Disadvantages include:

- Mechanically and operationally more complex than ullage recompression
- Propellant metering is required.

Choice. Ullage recompression was chosen based on design simplicity, operational simplicity, and cost.

Issues

Several important issues, summarized in Figure 7, were identified during the Phase I study. Resolution of these issues became important Phase II goals.

Phase I Results

- The ullage recompression method was chosen.
- Major interfaces were identified.
- The currently qualified hardware was found to be adequate for OOR.
- The dissipation of heat of compression during OOR was found by the analysis to be controllable.
- No major changes to current FSS/GRO berthing concepts were defined.

PHASE II — CONCEPT DEFINITION

Subsequent to the Phase I selection of ullage recompression as the preferred refueling method, the Phase II tasks required to define the concept were performed.

On-Orbit Refueling Configuration

Figure 8 is a schematic diagram illustrating the modifications required to incorporate refueling capability into the propulsion subsystem baseline. The proposed configuration requires adding four refueling service lines in parallel with the existing fill and drain lines. The refueling lines are fed from a common manifold that supplies filtered propellant from the orbital refueling system (ORS) tankage through a propellant/pressurant interface unit (PPIU). Latching valves in the refueling lines serve two functions: tank isolation (primary), and propellant cross-feed between thruster banks (secondary). This configuration eliminates the two cross-over lines between the PDMs in the baseline system.

In summary, adding the refueling capability will require the following additional hardware:

- Two isolation valves (add four refueling line valves and delete two cross-over valves)
- One propellant filter
- One PPIU quick-disconnect coupling
- As-required interconnecting plumbing, heaters, clamps, etc.

With the exception of the PPIU, no new components need to be added to the system. The refueling capability is incorporated by using the same filter and isolation valve components planned for the baseline feed system.

PPIU Development

It was assumed during the GRO OOR study that the PPIU interface connectors would be developed as part of the JSC/STS On-Orbit Refueling Study Demonstration Program. The PPIU must be designed for mate/demate under existing propellant line pressure, thus eliminating the need to vent the lines. The mate and demate of the PPIU will be designed with a high degree of operational reliability under worst-case-expected thermal and dynamic environments. The primary concern of JSC safety personnel in this EVA operation is the transfer of even small amounts of hydrazine (on the astronaut's suit) back into the pressurized cabin. The PPIU will be designed with a two-fault-tolerant, three-seal configuration.

GRO Command/Telemetry Modifications

The addition of two isolation valves to the GRO propulsion subsystem will require four more valve commands (two open and two close) to implement OOR. Valve telemetry status indicators for these two valves will also be required.

Thermal Response

Because of the inherent simplicity of the ullage recompression method, it is the favored approach for refueling the spacecraft on orbit. One problem, however, is the temperature rise of the pressurant during recompression. The rate at which propellant can be transferred is limited by the rate at which heat can be dissipated by the ullage gas such that safe temperature and pressure limits are not exceeded.

The ullage compression was analytically simulated using a finite difference thermal model to represent the tank and the propellant/pressurant. The tank shell and ullage gas were nodalized as illustrated by Figures 9 and 10. To simplify the analysis, the tank was modeled as a cylindrical shell with a thin, constant area piston representing the elastomeric diaphragm. The tank shell was divided into six cylindrical nodes of varying thickness along its length, and four equal-volume annular nodes on the gas end. Similarly, the gas was divided into five equal volume nodes radially and nine axially. The incoming propellant was assumed to be an isothermal heat sink at 60°F. Since the thermal resistance across the diaphragm is negligible compared with the resistance through the gas, the diaphragm was assumed to be at the same temperature as the propellant.

Conductances were defined between nodes within the gas, and between the gas and the tank wall and the propellant. The exterior surface of the tank was assumed adiabatic, although the heat capacity of the shell was considered. This assumption is somewhat conservative. However, heat loss from the tank surface will be small because of the multilayer insulation (MLI). Conductors were also defined between tank nodes to account for heat transfer to the propellant along this path.

The heat of compression during a given time interval was calculated using relationships for the isentropic compression of an ideal gas. This provided a heating rate that was divided equally and impressed on each node representing the pressurant. The temperature response of the tank shell and the ullage was then determined by solving the difference equations.

The inital flow rate into the tank was calculated by assuming that a constant pressure supply (400 psi) is available for refueling. It was also assumed that the inital flow rate is limited only by the flow resistance in the refueling lines, the flow being driven by the pressure difference between the propellant supply and the receiver tank ullage. When the maximum temperature of the gas reached 200°F, the flow rate was reduced to maintain this upper limit. A simplified flow diagram of the analysis logic is provided in Figure 11.

This model was then used to evaluate the thermal response of helium and nitrogen pressurants. Using helium, it was determined that refueling could be accomplished within 4 to 6 hours and not exceed 200°F in the ullage. Using nitrogen, however, refueling would take between 8 and 11 hours in order to remain at a maximum of 200°F in the ullage. The difference is attributed to the higher thermal conductivity of the helium. Using nitrogen permits the loading of more propellant before reaching 200°F than helium (because of a lower ratio of specific heats); however, the flow rate required to maintain 200°F is about one-fourth the allowable using helium.

The analysis also reveals that a significant difference in temperature can occur between the tank wall and the ullage gas. The time constant for the propellant tank shell is greater than that of the gas, causing its temperature response to lag behind the actual gas temperature. This is particularly important because ullage temperature measurements will most likely be made by a thermistor bonded to the tank shell exterior. Care must be taken to establish an accurate correlation between the temperature measured at the thermistor and the maximum gas temperature. The thermal analysis indicates that the maximum tank temperature will occur near the pressurant inlet boss; therefore, this is the recommended location for the refueling thermistor.

The analysis indicates that the UR concept for OOR is sound. Assuming that the thermal constraints are observed, the OOR task can be accomplished in the allotted time.

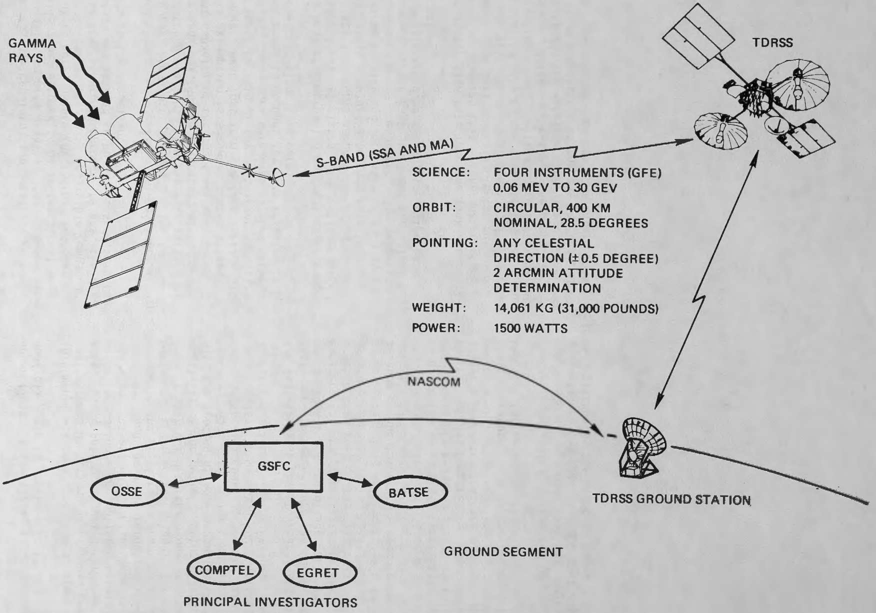

Figure 1. GRO Mission

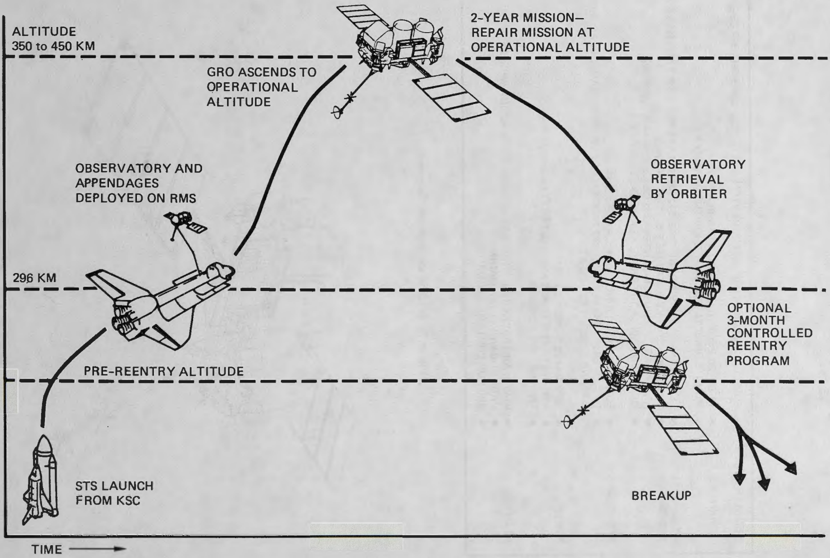

Figure 2. Mission Concept

INSTRUMENTS	• FOUR LARGE SCIENTIFIC INSTRUMENTS: EGRET, OSSE, COMPTEL, BATSE
STRUCTURE	• 10-BY-20-FOOT ALUMINUM I-BEAM PLATFORM • MOUNTS DIRECTLY TO SHUTTLE WITH TRUNNIONS
COMMUNICATIONS AND DATA	• TELEMETRY: 32 KB/S REAL TIME, 512 KB/S PLAYBACK, 1 KB/S CONTINGENCY • COMMAND: 1 KB/S AND 125 B/S (CONTINGENCY) • ANTENNAS: TWO OMNI ANTENNAS, ONE HIGH-GAIN ANTENNA • MODIFIED MMS CADH FOR PACKETS AND UTC CLOCK
PROPULSION	• FOUR TANKS HOLDING 2200 KG HYDRAZINE • THRUSTERS: FOUR 100-POUND THRUSTERS FOR ORBIT MANEUVERS, EIGHT 5-POUND THRUSTERS FOR ATTITUDE
POWER	• 1600 WATTS NOMINAL LOAD • 4000-WATT ARRAY ROTATES ±90 DEGREES ABOUT Y AXIS • TWO MMS MPS MODULES
ATTITUDE	• MMS STAR TRACKERS, GYROS, SUN SENSORS; ST REACTION WHEELS • MAGNETIC WHEEL UNLOADING • OBC FOR CONTROL ALGORITHMS

Figure 3. GRO Space Segment Summary

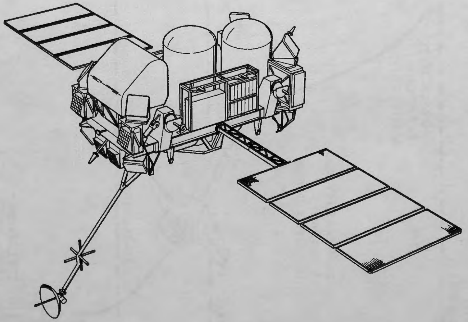

Figure 4. Gamma Ray Observatory

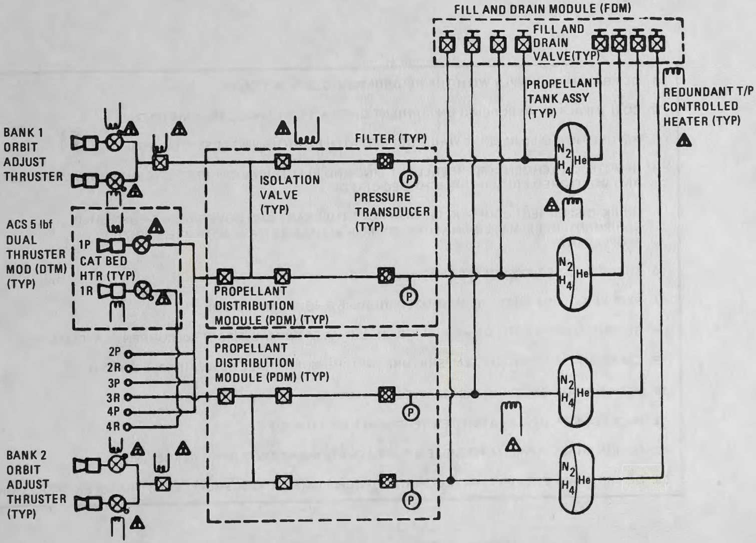

Figure 5. GRO Propulsion Subsystem Baseline Design

1. DESIGN SHALL COMPLY WITH THE REQUIREMENTS OF NHB 1700.7A
2. COST IMPACT OF REFUELING ON CURRENT GRO BASELINE SHALL BE MINIMIZED
3. REFUELING SHALL BE DONE WHILE DOCKED WITH FLIGHT SUPPORT SYSTEM (FSS)
4. REMOTE ATTACHMENT OF PROPELLANT LINE AND ELECTRICAL CONNECTIONS SHALL BE CONTROLLED AND MONITORED FROM AFT FLIGHT DECK (AFD)
5. QUICK-DISCONNECT COUPLING IS TWO-FAULT TOLERANT AND GOVERNMENT-FURNISHED EQUIPMENT (GFE). MATE/DEMATE OF COUPLING SHALL BE MADE WITH PRESSURIZED PROPELLANT
6. FUEL TRANSFER SYSTEM IS GFE
7. REFUELING TIME SHALL BE MINIMIZED (GOAL IS 6 HOURS MAXIMUM)
8. RECONFIGURING GRO FOR REFUELING SHALL HAVE MINIMAL IMPACT ON CURRENT BASELINE DESIGN
9. CAPABILITY TO MONITOR TEMPERATURE AND PRESSURE SHALL BE AVAILABLE ON AFD
10. DESIGN SHALL PRECLUDE ADIABATIC DETONATION
11. BACKFLOW OF OBSERVATORY FILTERS SHALL BE AVOIDED
12. DESIGN SHALL MINIMIZE POSSIBLE STS/GRO CONTAMINATION DURING REFUELING
13. DESIGN SHALL PREVENT FREEZE/THAW OF PROPELLANT DURING PROPELLANT TRANSFER OPERATIONS

Figure 6. Phase I Study Ground Rules and Assumptions

1. PRESSURIZATION
    A. ULLAGE RECOMPRESSION VERSUS VENT/PRESSURIZE
    B. HELIUM VERSUS NITROGEN
2. MAJOR INTERFACES. DEFINE ANY CHANGES TO THE PRESENT SYSTEM REQUIRED TO ACCOMMODATE REFUELING (ELECTRICAL, STRUCTURAL, THERMAL, TT&C, ETC)
3. HARDWARE CAPABILITY. DETERMINE WHETHER HARDWARE AS PRESENTLY QUALIFIED WILL BE CAPABLE OF MULTIPLE MISSIONS
4. THERMAL. DISSIPATION OF HEAT OF COMPRESSION DURING REFUELING OPERATIONS
5. ASTRONAUT INVOLVEMENT. DEFINE REQUIREMENTS FOR REMOTE REFUELING BASELINE
6. CAPTURE AND BERTHING. REFUELING MAY REQUIRE CHANGES TO CURRENT FSS BERTHING CONCEPT
7. OPERATIONAL SEQUENCE. ESTABLISH A PROCEDURE FOR MATE/DEMATE, CHECKOUT, AND PROPELLANT TRANSFER OPERATIONS, INCLUDING CONTINGENCY BACKUP AND SEPARATION PROCEDURES
8. TIMELINE
    A. DETERMINE HOW MUCH TIME EACH OPERATION WILL REQUIRE
    B. ESTABLISH REFUELING TIMELINE (GOAL IS 6 HOURS MAXIMUM)
9. GAUGING/METERING
    A. FIXED VOLUME DISPLACEMENT
    B. PVT DATA
    C. FLOWMETERS

Figure 7. Issues Identified During Phase I Study

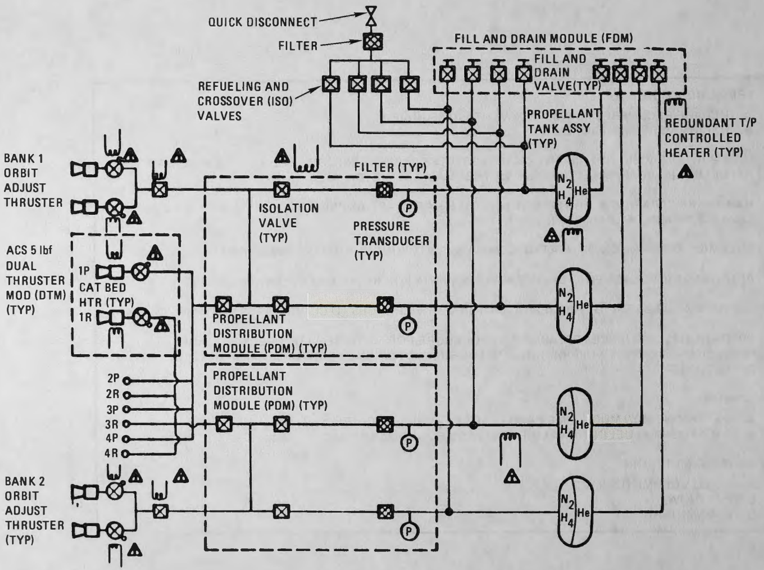

Figure 8. Refueling Schematic

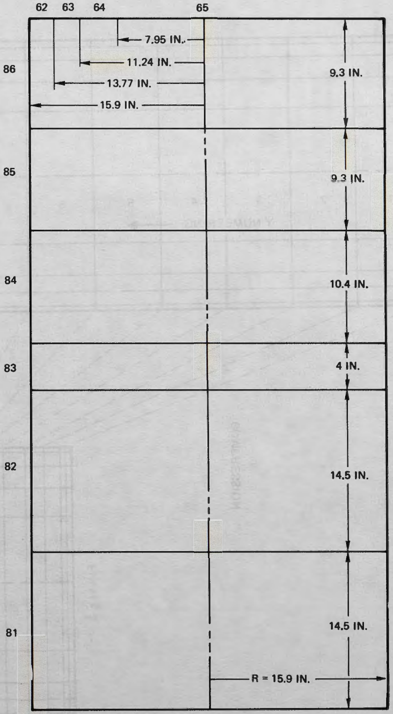

Figure 9. Tank Shell Nodalization

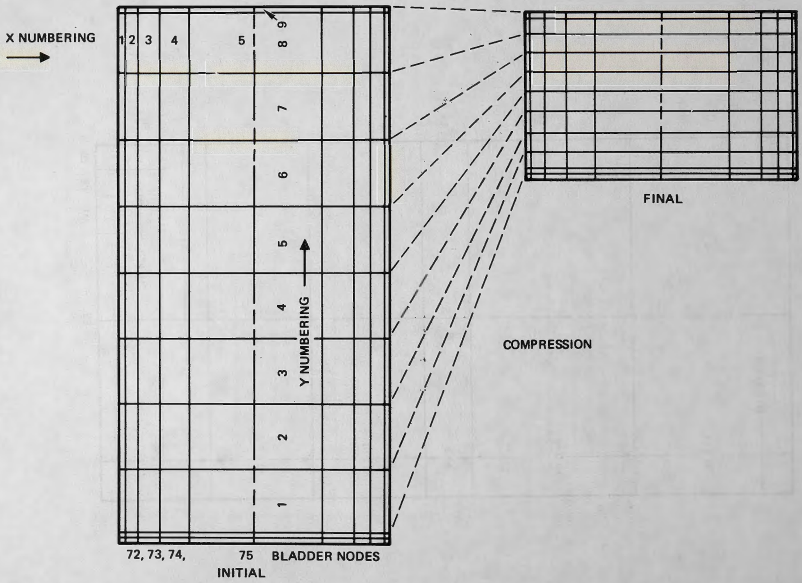

Figure 10. Ullage Gas Nodalization

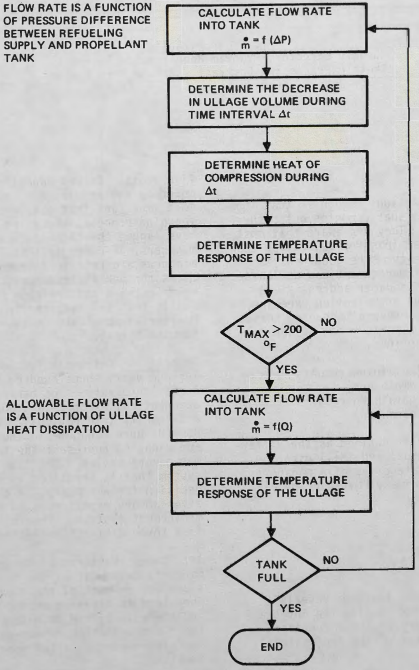

Figure 11. Thermal Approach